DEVELOPMENT OF CIRCULATORY SUPPORT SYSTEM THROUGH THE COLLABORATION OF U.S. AND U.S.S.R. PAST, PRESENT AND FUTURE

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During the last 21 years, the relationship between the U.S. and U.S.S.R. in general has not been harmonious. This has been the case until recently, in spite of all the political efforts extended by the political leaders on the both sides. Fortunately, during these 20 years, we scientists and clinicians devoting our life for the betterment of mankind have been working harmoniously together towards the common goal of treating the end-stage heart diseases by utilizing the most advanced engineering and scientific technologies.

I believe that our last 21 years of efforts resulted in not only our working together in medical science and technologies but also in our working together toward the peaceful coexistence of all mankind in the world. Today, I would like to present a summary of our efforts of the last 20 years in the field of circulatory support and artificial heart developments, present the current status, and I would like to project a future prospective on the subjects.

Past Efforts

The development of a mechanical pump to assist or replace heart function as a means of maintaining circulation in patients with irreversible cardiac failure has engaged the interest of investigators including ourselves for several decades. If I recall that it was approximately 40 years ago, I had developed the DeBakey Roller pump for circulatory support. This simple nonpulsatile pump was used primarily for cardiopulmonary bypass but also for circulatory assistance. Even though it is an old design, it was proven to be effective and is still the main workhorse for cardiopulmonary bypass.

Our artificial heart team after initial attempts to devise a means of total cardiac replacement turned its primary concern toward the development of a pump for support of the left

ventricle, i.e., a left ventricular assist device (LVAD)[1,2,3]. However, it was not until 1966, when a pulsatile pump, such as the one we developed together with the engineering talents of those from Rice University, was proven to be effective to salvage patients who required cardiac assistance. The left ventricular by-pass pump which we designed for this purpose was used in animals for two years to prove its efficacy and safety[4]. On this basis, we began its clinical application in patients who were critically ill with heart failure resulting from valvular heart disease (Figure 1). Following operation for valve replacement, these patients required temporary support. Utilization of the LVAD provided support until the heart recovered adequate function.

The first clinically successful use of our LVAD was performed in a 37 year old woman with severe manifestations of aortic and mitral valve insufficiency[5]. The operation was performed on August 8, 1966. Following replacement of the aortic and mitral valves by means of prosthetic ball valves, it became apparent that this patient could not be weaned from the cardiopulmonary by pass pump owing to heart failure, and the LVAD was installed. With a flow rate of about 1500 cc per minute by the LVAD, it became possible to restore cardiac function to a satisfactory level and remove the cardiopulmonary by pass pump. The LVAD was used to support the patients cardiac function over the next 10 days and at the end of this period, test of cardiac function showed that the heart had completely recovered and the LVAD was removed. The patient was discharged from the hospital about 10 ten days later and subsequently returned to her normal occupation as a hair dresser. Currently, this type of device was proven to be a life saving device for one out of 4 dying patients.

When the U.S. and U.S.S.R. Joint Artificial Heart Program was initiated, the value of a circulatory support system was not recognized by more than a half dozen investigators in the United States and only a few investigators in the U.S.S.R., including Dr. Shumakov in Moscow. I was grateful to President Johnson who initiated the U.S. Artificial Heart Program in 1964, and President Nixon who started the U.S.-U.S.S.R. Artificial Heart Program in 1972.

Our collaboration with Prof. Shumakov initiated immediately after this program. Our cardiac surgeon, Dr. George Noon, was dispatched to Moscow immediately and exchanged the

most up-to-date technology in circulatory assistance. Dr. George Noon was the first surgeon to implant an artificial heart in an experimental animal in Russia.

Current Status

Cardiac Assistance

During these 20 years, circulatory support technologies gradually became widespread. Currently, the use of cardiac assist devices is implemented for cases of resuscitation, cardiogenic shock, postcardiotomy syndrome, acute myocardial infarction, bridge to transplantation, and occasionally arrhythmia. The degree of support, purpose and duration must determined before proper device selection. Upon insertion, most devices must be supplemented with anticoagulants. In addition, nutrition must be normalized, infection prophylaxis provided and the device monitored to achieve a successful outcome.

Secondary organ dysfunction is a common occurrence which must be managed [6]. One solution is early application of the assist device. An adequate cardiac output of greater than 2.1 l/min per m^2 must be maintained. In addition, pharmacologic support with inotropic and vasoative drugs must be minimized and fluid and electrolyte balance optimized with fluid intake and colloid oncotic pressure normal. Active diuresis must be maintained and if needed, continuous arteriovenous hemofiltration should be performed. Nutritional needs must be met, and organ systems supported and treated as indicated. Anticoagulation is added when necessary.

Cardiac Assist Devices

Intra-Aortic Balloon Pump

The intra-aortic balloon (Figure 2) is the simplest of the devices used, and it can be used alone or in combination with another pump such as the BioMedicus pump. It provides limited support and it does not have any significant reserve if there are arrhythmias or sever pump failure. It can be used for days to weeks. The longest that a patient has been supported at the Methodist Hospital with an intra-aortic balloon has been 7 weeks.

Percutaneous Cardiopulmonary Bypass

Another type of assist that is used is the percutaneous cardiopulmonary bypass (Figure 3). This is used for resuscitation for example following myocardial infarction, pulmonary embolus, arrthymias or cardiac rejection. It is also now being used in patient for support during percutaneous balloon angioplasties. It is also used in extracorporeal membrane oxygenation (ECMO). Percutaneous cannulation can be used as a ventricular assist without an oxygenator, with trans-septal left atrial cannulation. The Baylor group has not yet used it as an assist device, however, we do have the cannulas and are waiting for the first patient. In this application, the pump has to be on the side of the venous return so that the blood can be actively removed from the venous system. Gravity drainage, as it is used in the chest, is not sufficient to provide enough flow for this system so blood has to be sucked out with the pump.

BioMedicus Pumps

The BioMedicus pumps have been used in patients to provide left and right ventricular assistance. They can be used individually as left or right or biventricular (Figure 4) In performing this support, the cannulas for the left ventricular assistance are placed through the left atrium, remaining in the atrium, or threaded down into the ventricle, and are then returned through the ascending aorta. The right ventricular bypass inflow cannula is threaded into the right atrium or into the ventricle and the outflow is into the pulmonary artery, either directly into the artery or through the right ventricle, across the pulmonary valve into the pulmonary artery. The chest is closed in these patients after the procedure and the cannulas are brought out in a subxiphoid position. At Baylor, this device was used in 148 patients (120 males and 28 females), ranging from 15 to 84 years or age, the average being 56. The reasons for the assist were postcardiotomy, the common, in 89 patients, acute myocardial infarction in 9, cardiac graft failure in 21, bridge to transplant in 14, post PTCA (percutaneous transluminal coronary angioplasty) emergent in 2 and other in 12.

DeBakey Paracorporeal Device [5]

As previously mentioned, Dr. DeBakey's paracorporeal air-driven pump was first used back in the 1960's in six patients, with two long term survivors.

Novacor Device

The Novacor pump was used in a total of 15 patients (13 males and 2 females), ranging from 16 to 66 years of age. They were pumped from 1 to 155 days. Six of these patients (40%) required a BioMedicus right ventricular assist (Figure 5). The right ventricular assist was employed for 1 to 10 days (average 5.6 days).

Total Artificial Heart [7]

The total artificial heart, Symbion TAH, was used as a bridge to transplant in four patients at Baylor, all males. The period of pumping varied between 3 and 105 days. In patients with the total artificial heart and the Novacor, the function of the ventricles could be determined using radionuclide imaging, and the cardiac output could be estimated.

Summary

Approximately 1000 circulatory assist devices of various types were applied in patients who suffered from post-cardiotomy cardiac failure. Approximately one quarter of patients were salvaged by this technology. In addition, various types of circulatory assist devices and artificial hearts were applied for the bridge-to-transplant patients in over 1,000 cases. Approximately 60% of the patients who received various types of assist devices and 45% of the patients who received various types of total artificial hearts had successful heart transplantation and survived. In Table 1, there is a summary of Baylor's experiences using various types of circulatory support systems applied in patients.

Future Perspectives

The success rates for use of circulatory assistance are revealed to be equal with the currently available blood pumps, either pulsatile or nonpulsatile. In order to increase this rate, we in the Baylor team intend to introduce more effective, safe and durable circulatory assist systems. We believe that a good nonpulsatile pump system will be developed and almost all the bridge-to-transplant patients and patients who suffer post-cardiotomy circulatory failure will be maintained by these types of devices.

We are devoting our effort to develop a better nonpulsatile pump. One of the reasons we need to develop a safe and easy to operate pump is that now cardiopulmonary bypass is a tool not only for a cardiovascular surgeon, but also for cardiologists, radiologists and anesthesiologists in a combination of angioplastic procedures.

Recently centrifugal pumps tend to be used in the majority of short-term circulatory assistance cases. Thus, we put our efforts toward developing a second generation DeBakey pump. We call this group of pumps a two-day pump. Recently we have developed a cable-driven centrifugal pump[8]. Figure 6 demonstrates a pump, a driving cable and a driving console. This console is interchangeable with a standard roller pump. Figure 7 shows the disposable centrifugal pump body. Its diameter is 50 mm and is very small. Its hemolysis rate is extremely low compared to the best nonpulsatile pump available, namely, the BioMedicus pump. Even though the level of hemolysis is within the normal range, the free plasma hemoglobin level generated by our pump has been demonstrated to be lower than that of BioMedicus pump. This pump is now waiting FDA approval in the U.S.A. while it was already approved for clinical studies in Japan.

Unfortunately, all of the currently available rotary pumps have a rather short life for pumping blood. The formation of protein deposits around the shaft of the pump at the shaft seal area is unavoidable. This buildup causes the rotary motion to freeze. The only way to extend its life is to eliminate the shaft seal. We achieved this task by applying the gyroscopic principal to rotate an impeller/rotor[9]. Figure 8 is the picture of a gyropump and Figure 9 is the cross-section of a gyropump. A rotor impeller is suspended by a pivot bearing at the bottom. This

rotor impeller is rotated by an outside motor. As you can see, there is a permanent magnet imbedded in the impeller. The initial in vivo studies have already resulted in a successful 20 day implant in a calf.

We are also developing a nonpulsatile pump with NASA engineers here at Baylor. A small axial pump was proven to be effective in pumping up to 8 liters of blood while maintaining a very low level of hemolysis.[10,11,12] We believe these types of nonpulsatile pumps will be effectively developed to provide continuous cardiac assist for up to 6 months. An implantable version of the axial flow pump is seen in the photograph of Figure 10. A brushless DC motor stator is seen in the middle of the flow tube. On either end of the flow tube are clamp rings which serve to hold internal pump components in place. Figure 11 is a photograph of an exploded view of the implantable pump. At the bottom of the photograph are the internal components of the axial pump. These components include from left to right, a clamped flow straightener which serves as a front bearing holder, a spinning inducer and impeller, and a clamped flow diffuser which also serves as a rear bearing holder.

Figure 12 is a schematic of the axial flow pump. The spinning inducer/impeller is held in place by a ceramic bearing in front and back. The inducer provides additional flow and pressure and prerotates the fluid entering the impeller flow field. The inducer/impeller acts as both a pumping element in the flow tube and the rotor of a brushless DC motor. The six blades of the impeller each hold 8 separate rod shaped magnets which are clearly visible in the photograph of Figure 11. Each of these sets of 8 magnets act as a pole of a 6 pole brushless DC motor rotor. The flow diffuser located behind the impeller serves to hold the rear bearing. The diffuser converts the tangential flow generated by the inducer/impeller to an axial flow.

The advantages of this pump include small size (25 mm diameter by 75 mm length), weight (53 grams) and displacement (15 cc). In addition the electromechanical drive system is incorporated into the impeller. This results n a compact and efficient system and allows a design which does not require an external shaft feed through, thus eliminating a common site for thrombus formation.

Based upon results obtained to this point we have developed an axial flow pump capable of pumping 5L/min against 100 mm Hg using less than 10 watts of power. A preliminary two day calf implant has been achieved and more are expected in the future.

Conclusion

I believe at this time our resources are limited and we should not reinvent the wheel. It is becoming more and more important to have all the talents available in the world working in this field cooperating together for the final goal of establishing a totally implantable cardiac prosthesis.

Before closing, I would like to stress that 20,000-60,000 patients in the U.S.A. alone need a substitute heart. Only 10% of these dying patients can receive a heart transplantation. The need for the permanent circulatory support system for clinical application is considered to be urgent. I would like to propose, not only for U.S. and Russia, that we have to have a united effort to help each other in the world to establish this goal.

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Table 1. Summary of Baylor's experience with various types of circulatory support systems applied to patients.

Device	Patients
Intra-aortic balloon pump (IABP) (1971-1991)	1757
Roller Pump (1971-1988)	94
DeBakey VAD (1963-1966)	6
Liotta, Hall, Crawford (1963)	1
Symbion/Jarvik (1987-1989)	4
Novacor (1987-1992)	14
Biomedicus (1985-1992)	148

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